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Titan Turtle:

NIAC Phase II Design for a Submersible Vehicle for Titan Exploration

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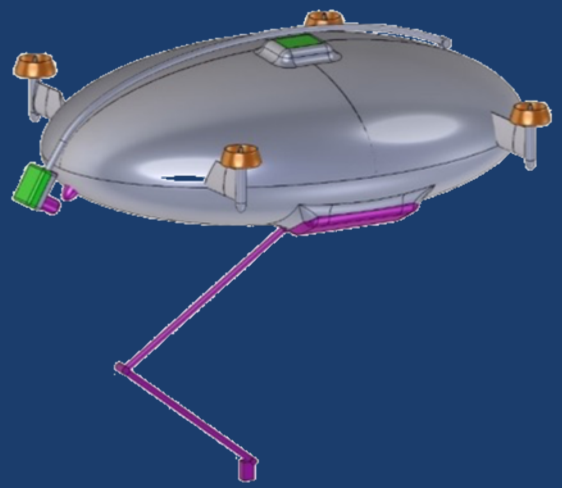
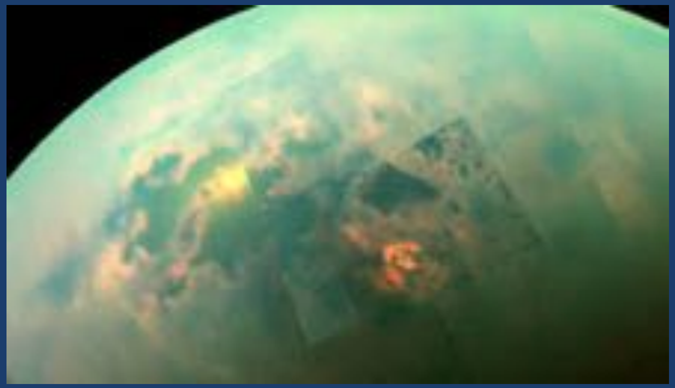


NASA Innovative Advanced Concepts



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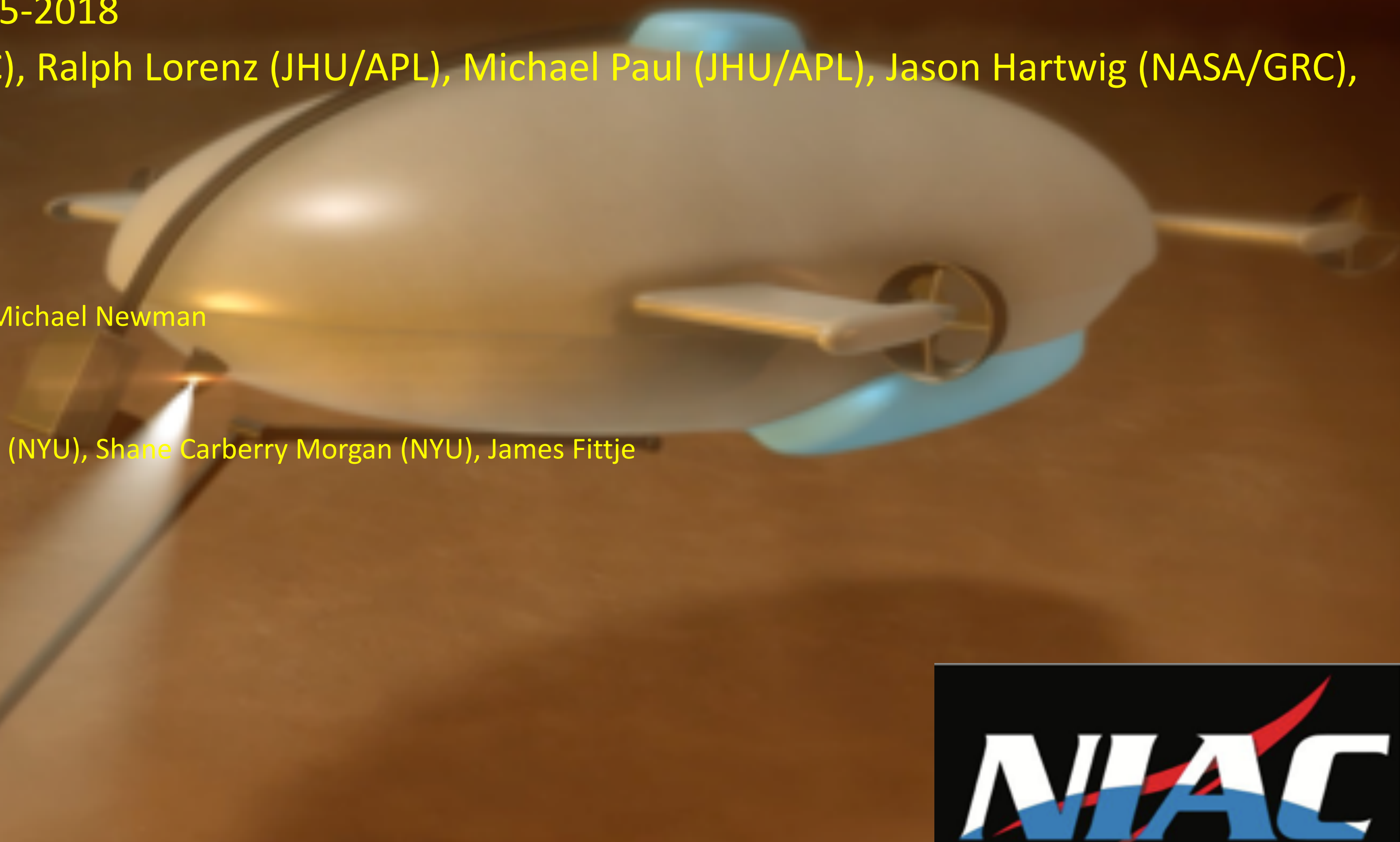
Titan Submarine Team



Customer: NASA NIAC, Phases I & II, 2015-2018

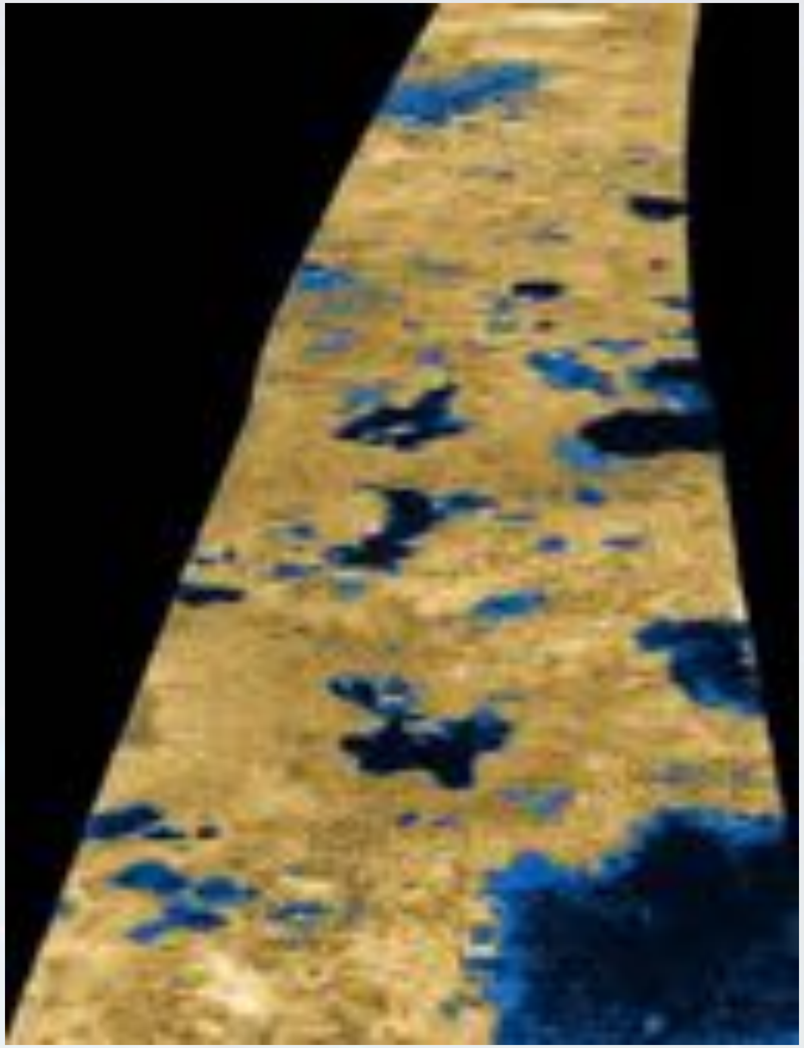
- Concept PIs: Steve Oleson (NASA/GRC), Ralph Lorenz (JHU/APL), Michael Paul (JHU/APL), Jason Hartwig (NASA/GRC), Justin Walsh (PSU/ARL)

  COMPASS Design Team
  - Lead - Steve Oleson
  - Science– Ralph Lorenz (APL)
  - System Integration, Conops, Launch vehicle – J Michael Newman
  - Mission – Steve McCarty
  - GN&C - Mike Martini
  - Hydrodynamics and Propulsion – Iskender Sahin (NYU), Shane Carberry Morgan (NYU), James Fittje
  - Mechanical Systems –John Gyekenyesi
  - Thermal - Tony Colozza
  - Physics: Geoffrey A. Landis
  - EDL – Evan Roelke (Georgia Tech)
  - Power - Paul Schmitz
  - C&DH, Software – Amee Bogner
  - Communications – Robert Jones
  - Configuration - Tom Packard
  - Cost – Tom Parkey, Elizabeth Turnbull
- University Support: Washington State - Cryogenic Testing: Ian Richardson

NIAC
NASA Innovative Advanced Concepts

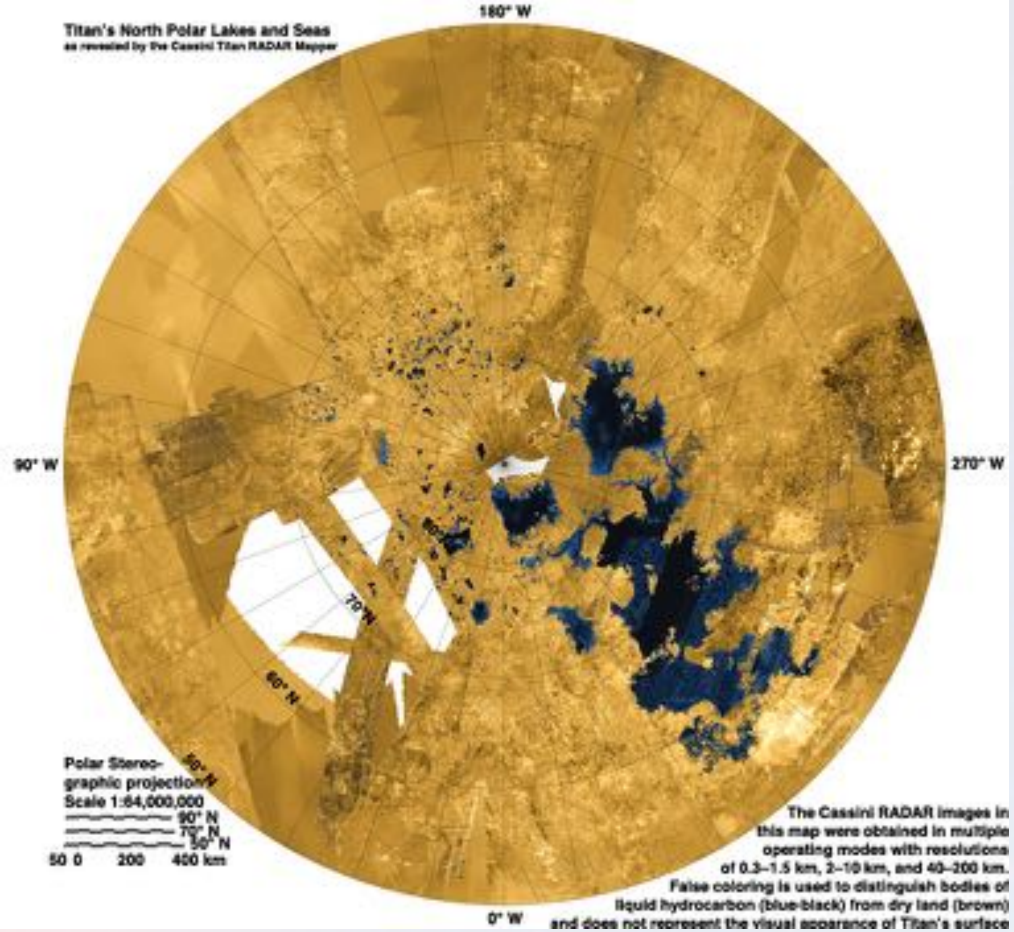
Titan– the *other* world with open liquid bodies on the surface

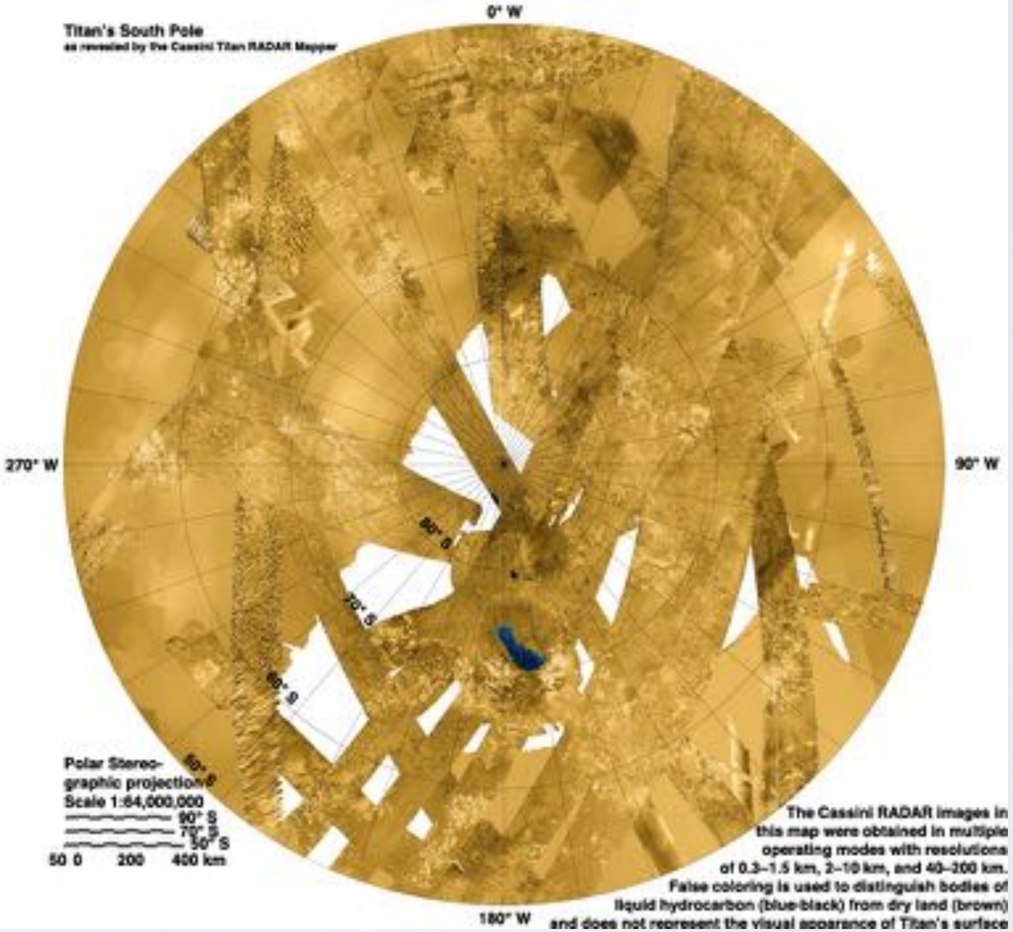
- Saturn's moon Titan is the only moon in the solar system to have a dense atmosphere, and the only body other than the Earth to have bodies of liquid on the surface.
- The Titanian oceans, however, are not composed of water, like Earth's oceans, but are in the form of a series of hydrocarbon (methane and ethane) lakes, covering a surface area of over 500,000 km^2.



Titan's hydrocarbon lakes shown in false color, as viewed by the Cassini radar.

Titan’s Seas



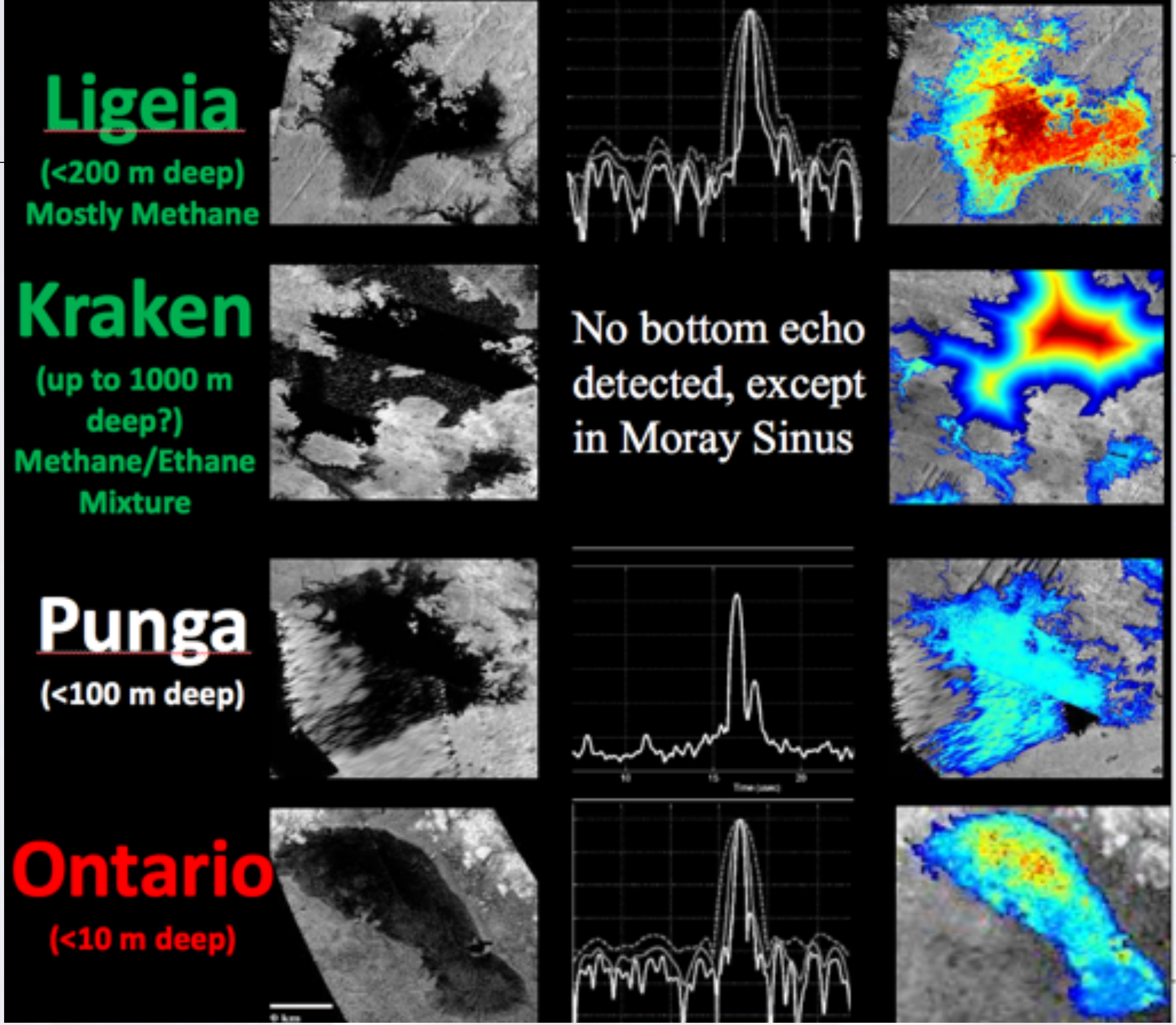


- 3 Seas in North: **Kraken Mare, Ligeia Mare and Punga Mare** (~1000, 400, and ~200 km across respectively) Only one large lake in the south, Ontario Lacus.

How Deep Are the Seas?

From Cassini Data:

✓Kraken and Ligeia in the north are the best Submersible Targets

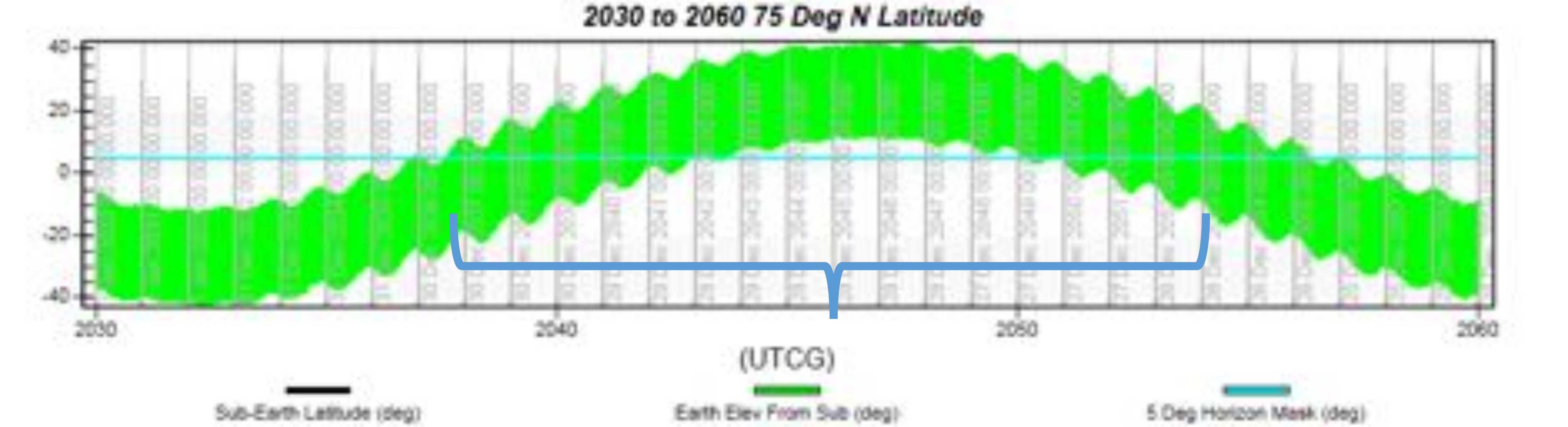


Ability of Cassini radio waves to penetrate seas hints as use of RF for submerged Comms!

Earth vs. Titan Seas

Parameter	Earth	Titan
Material	Water	**Liquid Ethane & Methane** (% mixture?, High N_2 gas solublity)
Density	~1000 kg/m^3	**~650 kg/m^3 / 450 kg/m^3**
Temp	~0 to 30 °C	**-178 °C**
Viscosity	1000 µPa-s	200-4000 µPa-s
Gravity	1 g	0.14g
Depth	1000's m	200 m Ligea, 1000 m? Kraken
Pressure	~1 Bar / 10m depth	**~ 1 Bar / 115m**

When to Go: Seasons on Titan



- Direct Earth Communications and Light to image the shore AND Best to arrive in summer! (Summer ~ **2045**)
- IF we have an orbiter for relay and submerge during 'night' (Spring ~**2040**)
- **Trips to Saturn take ~6-9 years so we need to launch early to mid 2030s**

Science Surfaced and Submerged

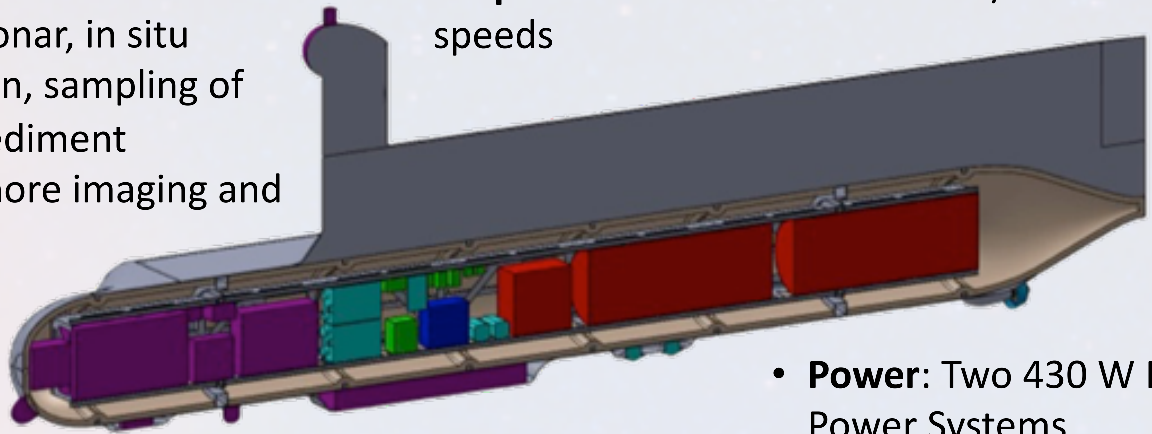
- *Titan is a target for the Ocean Worlds Exploration Program*
- *Titan's seas, while liquid methane based, are a key part of a weather system like ours*
- *Sampling of seafloor sediments could reveal Titan's Climate History*

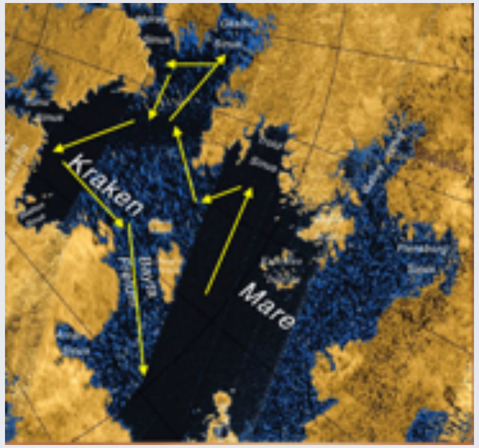
	Instrument	Technique	Rationale
Threshold	**Chemistry Analysis Package (CAP)**	Liquid sample acquisition system coupled to multiple analytic instruments (nominally GCMS)	Measure bulk and trace constituents of sea at different locations and depths
	Surfaced Imager (SI)	Panoramic CCD imager (gimballed?) on upper structure	Observe sea surface, shoreline geomorphology, clouds, atm.optics
	Depth Sounder (DS)	Single down-looking Acoustic sounder	Low frequency (10-20 kHz) to measure depth to bottom, possibly detect layers, bubbles etc.
	Meteorology Package (MET)	Pressure, Temperature, Wind speed and direction, methane humidity	Record meteorological variability, forcing of air:sea exchange
	Physical Properties Package (P3)	Sea temperature, speed of sound, dielectric constant and turbidity	Structure of liquid column (stratification), suspended sediment, air-sea exchange, local variations in bulk methane/ethane
Desired	**Sidescan Sonar (SS)**	Side-looking acoustic imaging array	Acoustic imaging of seabed morphology
	Undersea Imager (UI)	medium-field CCD imager equipped with multicolor illuminators	Optical imaging of seabed (Combine with SI if vehicle orientation permits?)
	Benthic Sample Acquisition (BSA)	Grinding/suction system to ingest solid or semi-solid seabed materials	Deliver seabed sediments to CAP instrument
	Infrared Spectrometer (IRS)	Fiber-coupled Near- and Mid-IR absorption spectrometer	

Phase I Sub Concept: Big and Fast!

- **~ 100 kg Autonomous Science** Sonar, in situ exploration, sampling of bottom sediment
- Surface shore imaging and weather

- **Propulsion**: Four motors for 1 m/s submerged and 1 m/s surfaced speeds



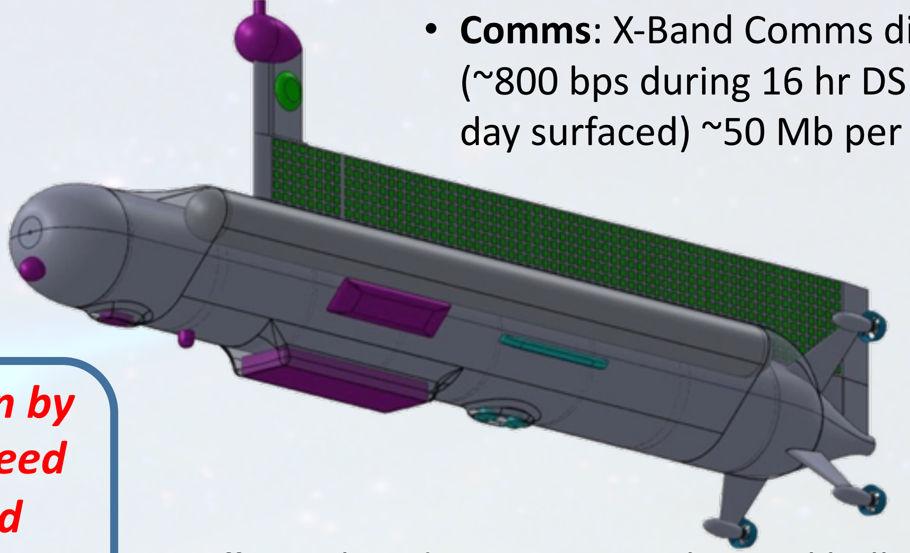


- **90 day journey Kraken-1**

- **Power**: Two 430 W Radioisotope Power Systems

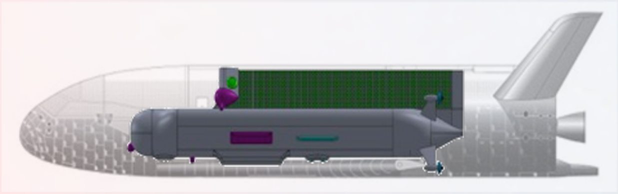
~ 6 m long, ~ 1400 kg

- **Comms**: X-Band Comms direct to Earth (~800 bps during 16 hr DSN passes each day surfaced) ~50 Mb per day



- **Thermal**: Interior RPS heated, 3cm aerogel insulation, 300 W/m^2 through skin, outer systems cryo-capable (-178 °C)
- **Navigation**: IMU, sun direction, earth tracking, liquid velocity doppler, sonar scanning

Medium Class Launcher using an X-37 derived lifting body

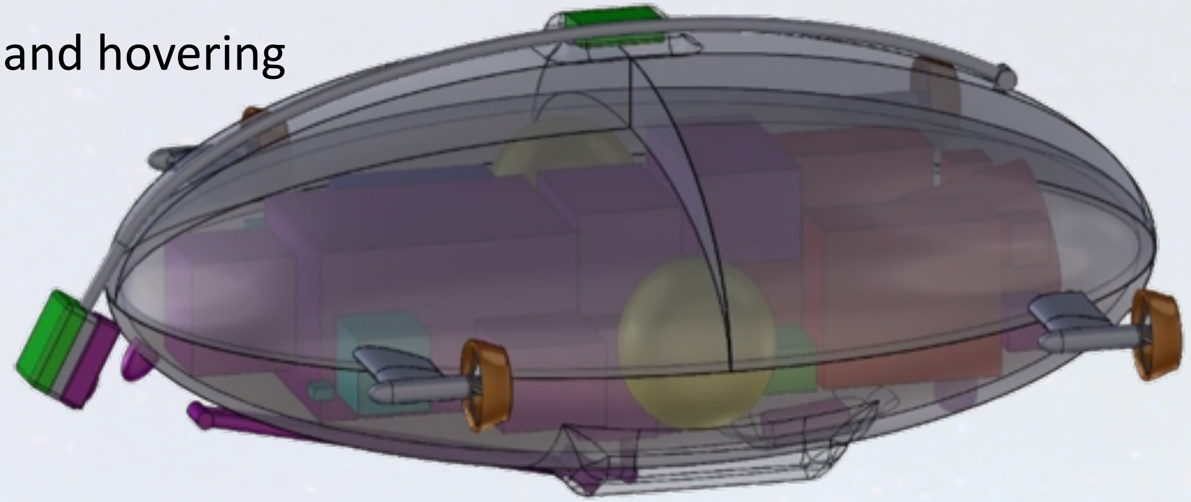


Power/Size/Mass/Aeroshell: Driven by DTE communications and 1 m/s speed (efficient long narrow shape) and Science mass/hover needs, needs new aeroshell

- **Ballast**: Closed Ne system with metal bellows ballast tanks submerging and hovering down to 1000 m at pressures ~ 10 bar, Ethane/Methane Sea Mixture

Phase II Titan Turtle: Orbiter Supported

- **Propulsion**: Four motors
- 0.3 m/s submerged
- 0.2 m/s surfaced speeds and hovering

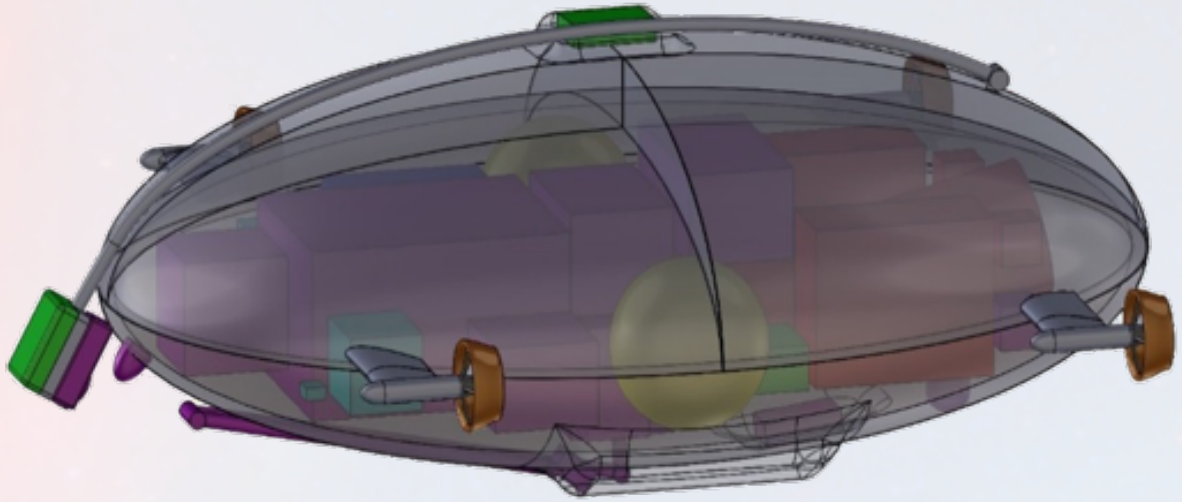


~ 2 m long, ~ 500 kg

- **Power**: Single 90W eMMRTG

Providing orbiter relay (even when submerged!) and slowing speed to 0.2 m/s speed allows reducing mass by 3X and same science suite but ~20X data return, smaller shape allows use of SOA 4.5m aeroshell

Phase II Titan Turtle: Orbiter Supported

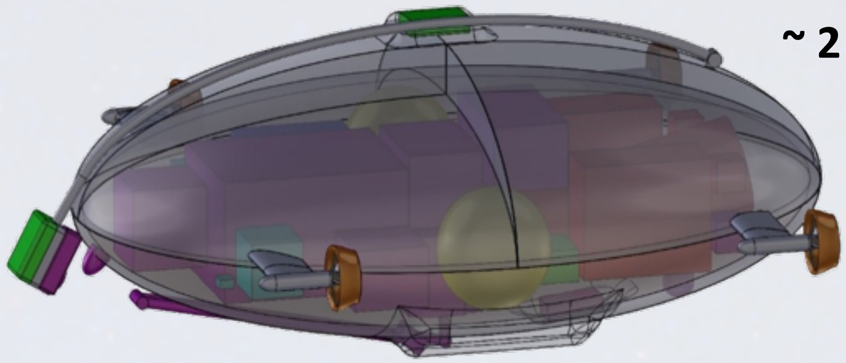


~ 2 m long, ~ 500 kg

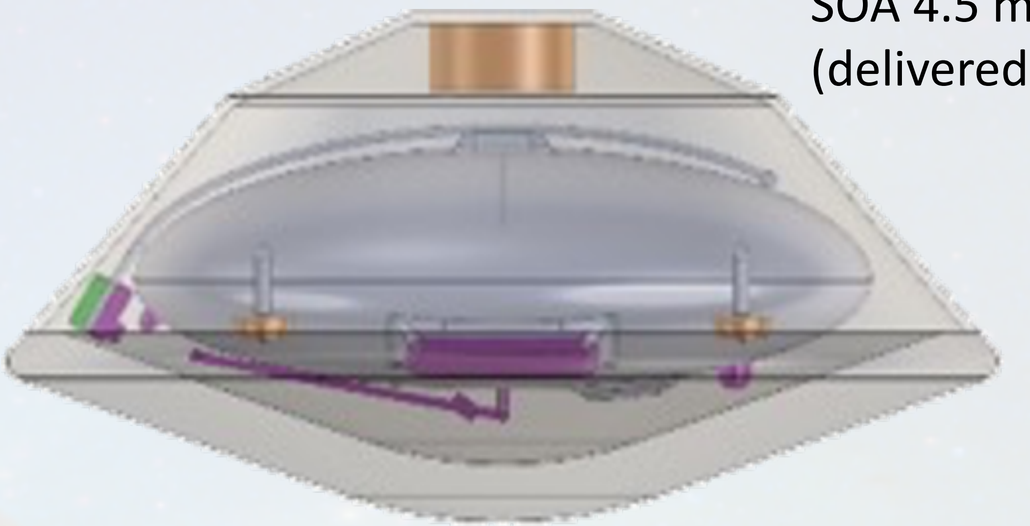
- 180 day Journey around/beneath smaller Ligeia Mare

Phase II Titan Turtle: Orbiter Supported

- **~ 100 kg Autonomous Science** Sonar, in situ exploration, sampling of bottom sediment
- Surface shore imaging and weather
- **Thermal**: Internal RTG waste heat, 2.5 cm aerogel insulation, 300 W/m^2 through skin
- **Navigation** using IMU, **Orbiter** tracking, sonar scanning



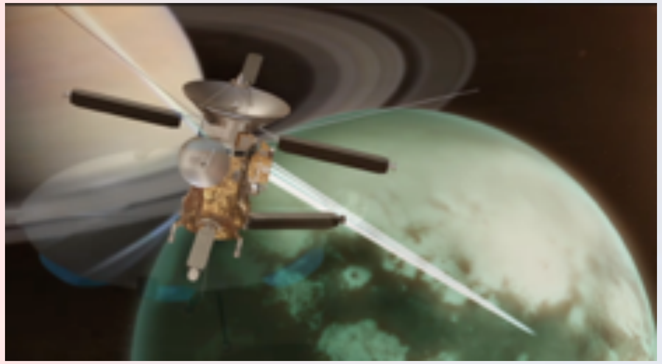
~ 2 m long, ~ 500 kg



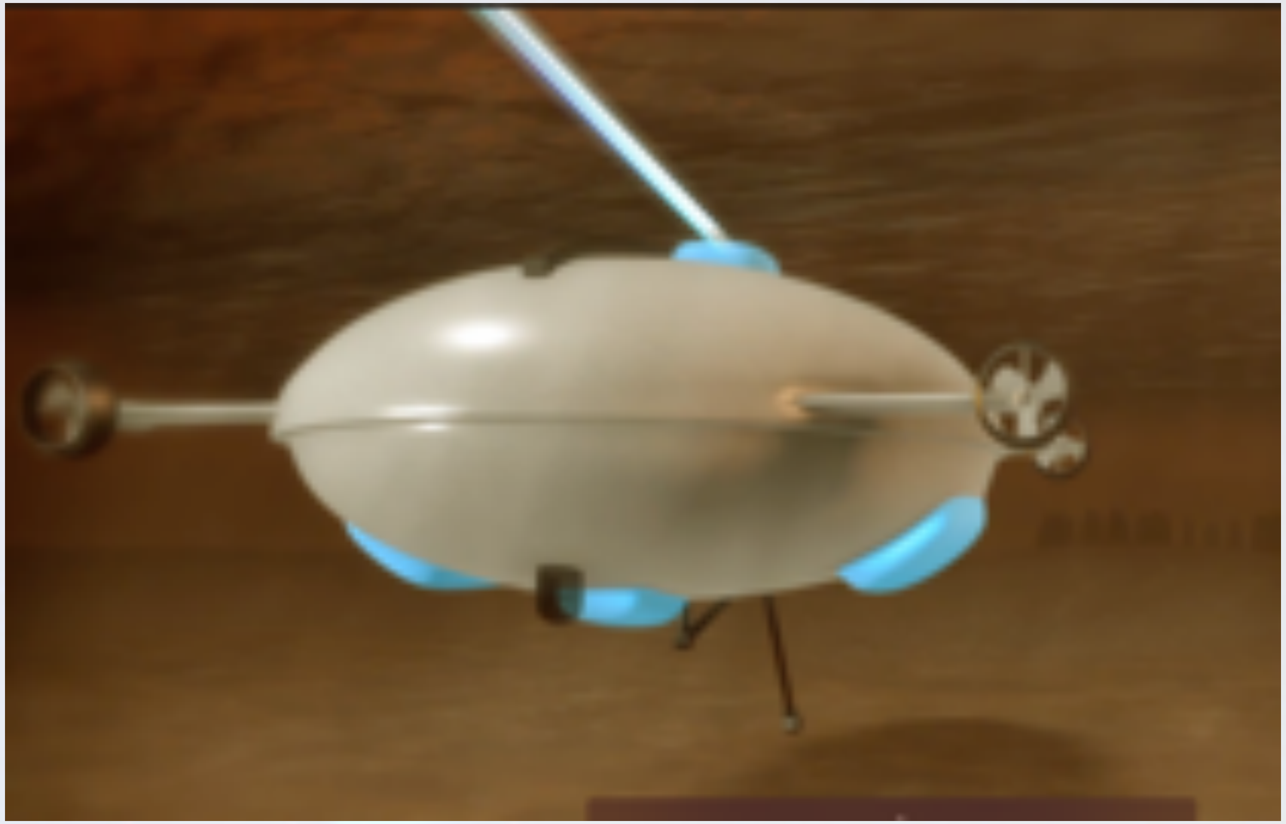
SOA 4.5 m Aeroshell (delivered by orbiter)

Titan Turtle submersible (top), and vehicle inside 4.5-m aeroshell for entry (bottom)

Phase II Titan Turtle: Orbiter Supported

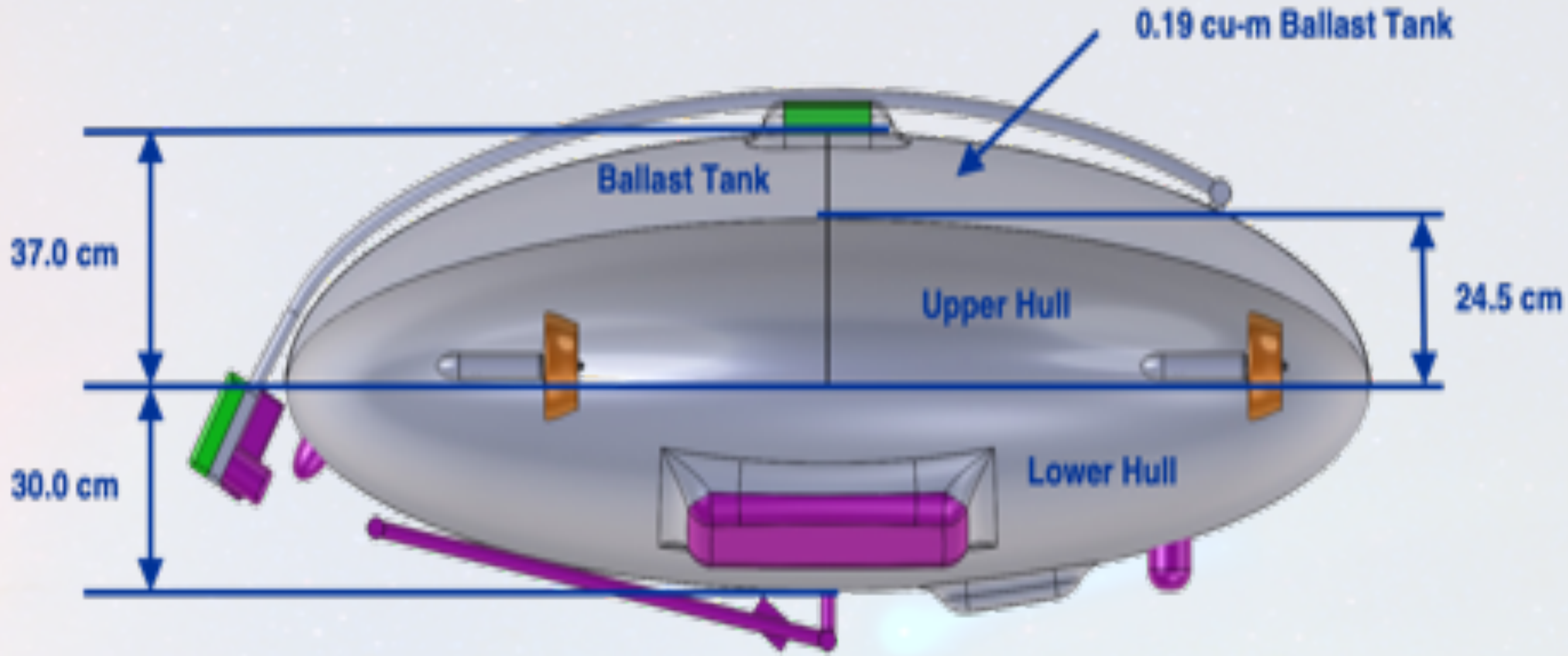


- **Comms**: UHF-Band Comms (~100 kbps during five, 30 min 1500 km orbiter passes each day surfaced: ~ 1Gb/day)



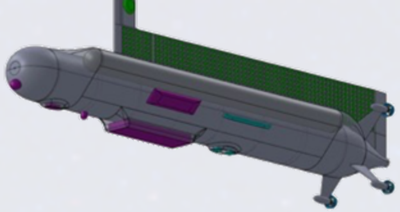
- **Ballast**: Pressure vessel with external, closed He system ballast tanks to allow for submerging and hovering up to 200 m at pressures < 5 bar (mostly Methane Sea)

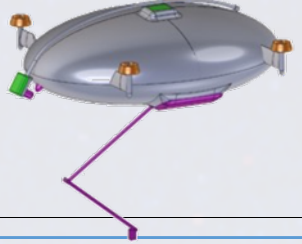
Phase II Titan Turtle: Orbiter Supported

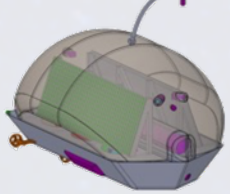


Phase II Titan Turtle: Orbiter Supported

Technology Needs



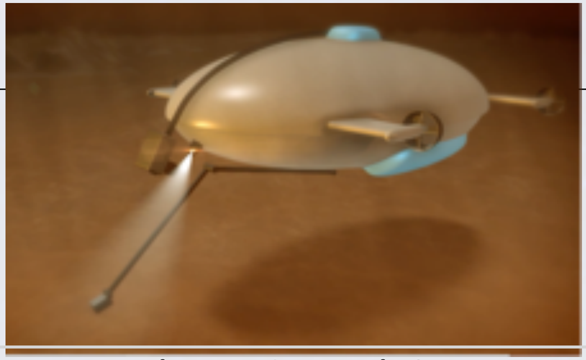




Item	Phase I Stand-Alone Sub	Phase II Orbiter Supported	Phase II Ship with Dropsondes
Science	External Cryogenic Science Instruments		
Attitude, Location	Submerged navigation using IMU/floor tracking	Orbiter supported submerged, IMU	DSN Supported Cryogenic Sun sensors, terrain
Command	Autonomous Operations		
Comms	Cryogenic exposed X-band DTE phased array antenna	UHF Comms through cryogen	Cryo UHF comms from Dropsonde
Power	~ 400 W RTG or SRG	~ 100 W eMMRTG or SRG	~ 100 W eMMRTG or SRG
Thermal/Mech	Aerogel internal Insulation, Cryogenic liquid **external** structures/mechanisms		
Propulsion	Pressure Drop N_2 Efferevescence, Cryogenic motors		
EDL	New, Long Aeroshell	SOA	
Ballast system	Cryo Valves/Expendable Ballast Gas (He) or Metallic Bellows (sized for sea mixture uncertainty)		None

Extraterrestrial Submarines

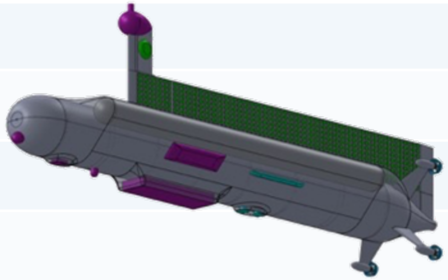


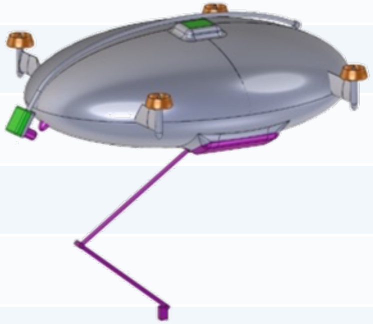



	Common to Cryogenic and Ice Covered Seas	***Unique to Cryogenic Seas***	***Unique to Ice Covered Seas***
Science	Both subs will need very robust science instruments to handle ‘first contact’ environment interaction	Instruments operate at -178°C	Instruments similar to terrestrial subs
Autonomy	Due to communications lag both subs will need to operate autonomously		
Navigation	Velocimeters could be used for both subs	Titan easier given the viewability of the sun and the RF transparency of the seas	Some seas may have a magnetic field
Communications	Both Subs could benefit from a sonar based comm system (albeit very low data rate)	Titan easier given an RF link	communications through ice shell may be difficult
Ballast	Both subs benefit from isolated pressurant or mechanical volume systems	Due to lower temperatures Titan sub will need to use He as a working ballast gas or metallic bellows	Water extraterrestrial subs could use other gases/fluids and non-metallic bellows
Size/Volume		Titan Subs can fit into SOA aeroshell	Must fit though a minimum diameter borehole!
Environment interaction	Both will need to be resistant to perhaps corrosive, contaminated environments	Subs outer instruments and equipment exposed to -178°C	Sub exposed to -150°C during transit thru top ~100 m of ice surface, 0°C in the sea
Power	An isotope or fission system will be needed for long term operation OR use tethered power (limits separation with mothercraft)	Isotope or fission power more important to keep sub warm	May need to melt ice
Propulsion	Providing propulsion in unknown seas will require robust systems with forgiving interfaces		

Earth vs. Titan Submarine

Parameter	Sea Horse UUV	Titan Submarine
Sea Material	Water	Liquid Ethane & Methane
Density	~1000 kg/m^3	~650 kg/m^3 / 450 kg/m^3
Temp	~0 to 30 °C	-178 °C
Viscosity	1000 μPa-s	200-4000 μPa-s
Depth	1000’s m	200 m sensed (design max set to 1000 m)
Pressure by depth	Every 10 m ~1 additional Bar	Every 115m ~1 additional Bar
Gravity	1 g	0.14g
Max Depth	1000 m (100 Bar pressure)	1000 m (~12 Bar pressure)
Max Range	550 km	5000 km
Endurance	72 hr	1 yr
Speed	2 m/s	1 m/s (max)
Power	Battery	Isotope
Navigation	GPS (surfaced) & IMU	Sun Sensor, Earth Tracking & IMU, orbiter support
Communications	Surfaced satellite ~ 800 km	Direct to Earth (phase I) ~ 1.5 Billion km
		via orbital relay (phase II) while submerged





Science Surfaced and Submerged

- *Titan is a target for the Ocean Worlds Exploration Program*
- *Titan's seas, while liquid methane based, are a key part of a weather system like ours*
- *Sampling of seafloor sediments could reveal Titan's Climate History*

Must Do Science Floor

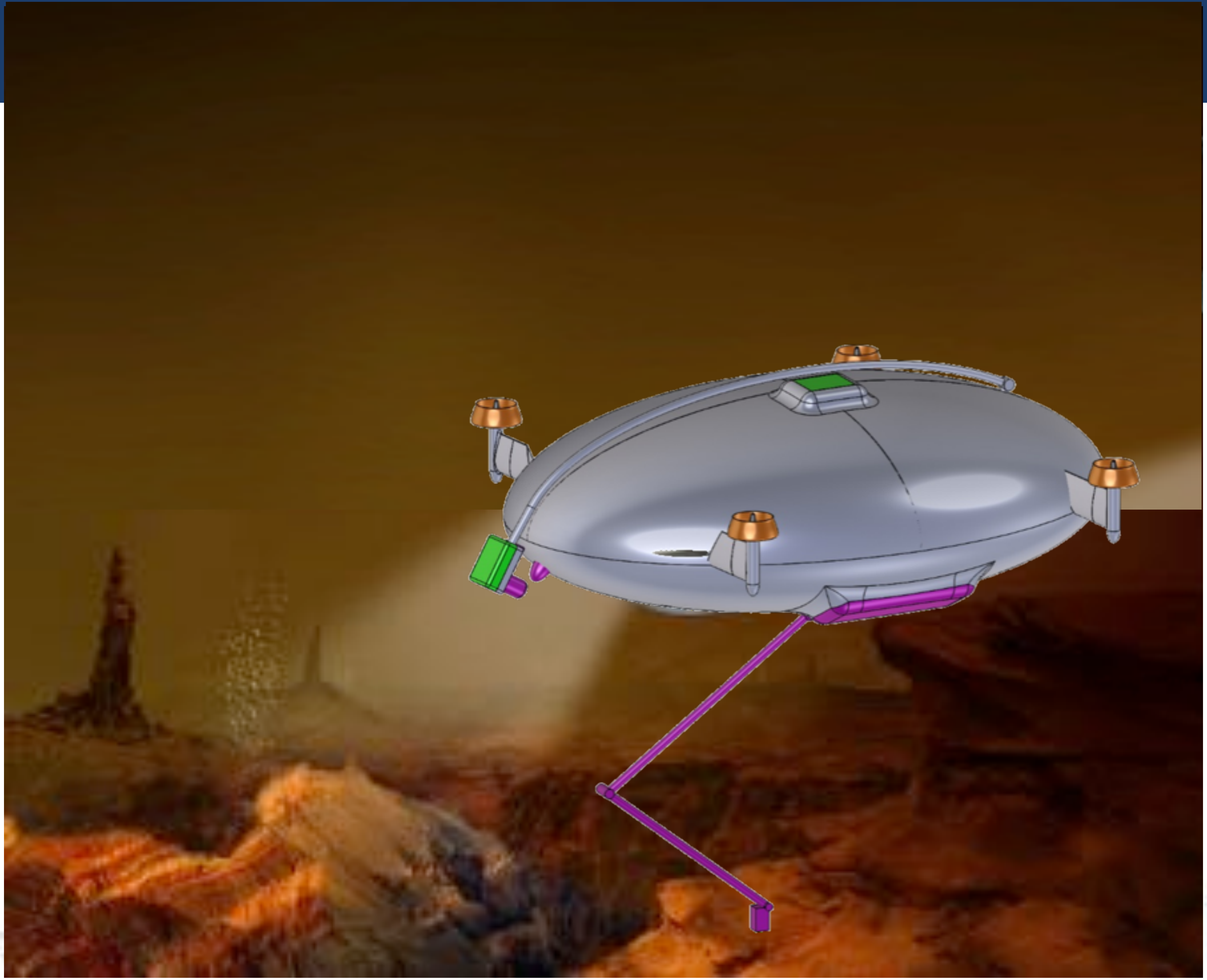
Added Science for Desired Baseline (intensive investigation of seabed)

	Instrument	Technique	Rationale	Requirements	Basis
Floor	**Chemistry Analysis Package (CAP)**	Liquid sample acquisition system coupled to multiple analytic instruments (nominally GCMS)	Measure bulk and trace constituents of sea at different locations and depths	Inlet isolated from heat source 40 kg. 80 W when sampling (2 hr; once per 2 days)	Curiosity/ SAM
Floor	**Surfaced Imager (SI)**	Panoramic CCD imager (gimballed?) on upper structure	Observe sea surface, shoreline geomorphology, clouds, atmospheric optics	Topside mount – 1m above sea surface 4 kg including housing. 10W when imaging (2 hr/day)	MER Pancam
Floor	**Depth Sounder (DS)**	Single down-looking Acoustic sounder	Low frequency (10-20 kHz) to measure depth to bottom, possibly detect layers, bubbles etc.	Nadir view 0.5 kg. 2 W continuous	TiME MP3, commercial fish finders
Floor	**Meteorology Package (MET)**	Pressure, Temperature, Wind speed and direction, methane humidity on Surface	Record meteorological variability, forcing of air:sea exchange	Topside mount – 1 m above sea surface, desirably away from heat source 3 kg. 6 W continuous	TiME MP3, Pathfinder ASI/MET terrestrial field instruments
Floor	**Physical Properties Package (P3)**	Sea temperature, speed of sound, dielectric constant and turbidity	Structure of liquid column (stratification), suspended sediment, air-sea exchange, local variations in bulk methane/ethane	Isolated from heat source 2 kg. 6 W continuous	TiME MP3/ Huygens SSP
Baseline	**Sidescan Sonar (SS)**	Side-looking acoustic imaging array	Acoustic imaging of seabed morphology	Bottom/side view. 10W when operating (8 hr/day)	Terrestrial UUV
Baseline	**Undersea Imager (UI)**	medium-field CCD imager equipped with multicolor illuminators	Optical imaging of seabed (Combine with SI if vehicle orientation permits?)	Forward view 3 kg including housing 20 W when imaging (1 hr/day)	Curiosity MAHLI
Baseline	**Benthic Sample Acquisition (BSA)**	Grinding/suction system to ingest solid or semi-solid seabed materials	Deliver seabed sediments to CAP instrument	Forward/lower view 5 kg. 50 W when operating (1 hr/2 days)	Phoenix rasp plus suction pump
Baseline	**Infrared Spectrometer (IRS)**	Fiber-coupled Near- and Mid-IR absorption spectrometer		8 kg. 20 W . 2 hr/day	miniTES, laboratory instruments
Engineering	**Navigation Systems (NAV)**	Pressure depth gauge, Inertial Measurement Unit, plus Doppler/DeltaDOR radio measurements	Infer ocean currents	(resources not book-kept under payload)	(various)

Summary: submersible

Main Subsystems	Basic Mass (kg)	Growth (kg)	Predicted Mass (kg)	Aggregate Growth (%)
Titan Submarine	***408.5***	***74.7***	**483.2**	18%
Science Payload	78.4	23.5	**101.9**	30%
Attitude Determination and Control	6.0	0.2	**6.2**	3%
Command & Data Handling	16.7	4.5	**21.2**	27%
Communications and Tracking	8.5	0.9	**9.4**	10%
Electrical Power Subsystem	71.5	4.2	**75.7**	6%
Thermal Control (Non-Propellant)	24.9	4.5	**29.4**	18%
Mobility	53.0	10.1	**63.1**	19%
Propellant (Chemical)	**0.0**		**0.0**	TBD
Structures and Mechanisms	149.4	26.9	**176.3**	18%
Element 1 consumables (if used)	**0.0**		**0.0**	
Estimated Spacecraft Dry Mass (no prop,consum)	**408.5**	74.7	**483.2**	**18%**
Estimated Spacecraft Wet Mass	408.5	74.7	483.2	
System LeveL Growth Calculations Titan Submarine				**Total Growth**
Dry Mass Desired System Level Growth	408.5	122.6	**531.1**	**30%**
Additional Growth (carried at system level)		47.9		**12%**
Total Wet Mass with Growth	408.5	122.6	**531.1**	

- The COMPASS design team incorporates an assumed growth in the mass estimates per ANSI/AIAA R-020A-1999 standards, with added growth carried at the system level to make total growth allocation 30%.



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COMPASS
COLLABORATIVE MODELING FOR PARAMETRIC ASSESSMENT OF SPACE SYSTEMS

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SHAPING THE FUTURE OF AEROSPACE

Acknowledgement

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